User Guide

Novoptel

PM1000 Polarimeter

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Revision history

Version	**Date**	**Remarks**	Author
0.2.1	26.01.2015	Draft version	B. Koch
0.2.2	27.02.2015	Register and operation description updated	B. Koch
0.2.3	04.03.2015	Operation description updated	B. Koch
0.2.4	11.03.2015	Description of measurement data files	B. Koch
0.2.5	21.07.2015	Description of PDL measurement	B. Koch

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Introduction

This user guide is valid and applicable not only for PM1000 but also for PM500.

The PM1000 polarimeter measures all 4 Stokes parameters at a rate of 100 MHz. The samples can be averaged to increase accuracy at low optical input power. Three normalization modes can be chosen. The calculated states of polarization (SOPs) are displayed on a Poincaré sphere at a connected monitor. This allows the polarimeter to be used without extra computer. It also enables realtime Poincaré sphere display at up to 50 MHz (at 100 MHz, only every second sample is displayed).

To explore the temporal evolution of the polarization, the user can switch the display to oscilloscope view. In this mode, the Stokes parameters are recorded in the polarimeter's memory and then plotted over time. The memory size is 4.3 Gb, i.e. 67 M polarization states can be recorded. The user can shift the oscilloscope plot and zoom into via the front control buttons.

The recording process can be triggered either externally by a BNC input signal or internally by defined SOP events. Pre- and post-trigger data is stored. The memory can be read out via the SPI or USB interface. To configure the polarimeter, a graphical user interface (GUI) can be started on a PC that is connected to the polarimeter by USB. The GUI can also load screenshots of the connected monitor to the PC and display the Poincaré sphere.

Rear panel

Figure 1 shows the rear panel of the PM1000.

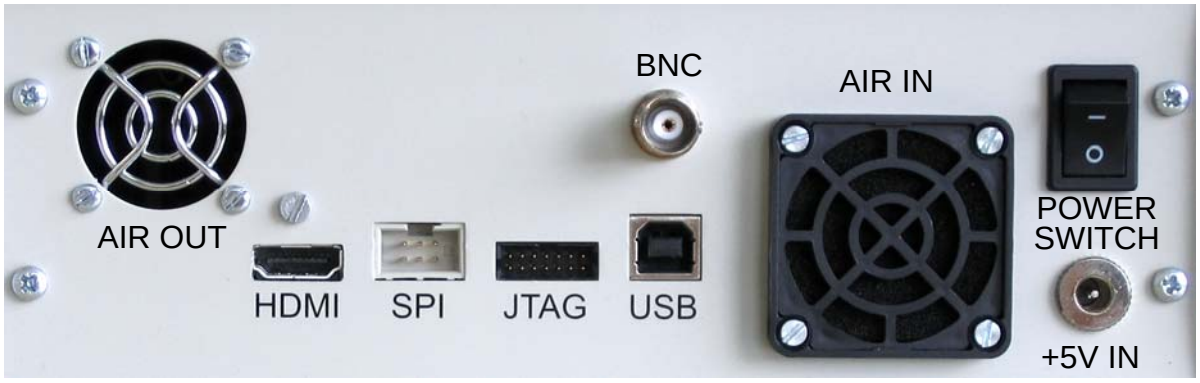


Fig. 1: PM1000 rear panel.

External monitor

A monitor can be connected to the HDMI output. The HDMI port outputs 1440 x 900 pixels at 60 Hz. A HDMI to DVI cable is included. It must be ensured that the connected monitor supports this input mode!

Fundamental PM1000 configuration

Optical frequency

The optical frequency value can be adjusted to match that of the analyzed optical input signal.

Averaging time (ATE)

For accurate SOP measurement at lower optical input powers, internal averaging after the 100 MS/s AD conversion is recommended. The averaging time is denoted by the averaging time exponent (ATE). 2^{ATE} samples are averaged and an effective conversion time of $2^{ATE}\cdot 10$ ns is achieved. ATE ranges from 0 (100 MS/s) to 20 (95.4 S/s).

Normalization mode

The PM1000 provides three choices for the normalization of Stokes parameters/ vectors:

- Standard normalization: Stokes vectors are normalized to unit length. Regardless of power and DOP, they appear at the surface of the Poincaré sphere.
- Exact normalization: Stokes vectors are normalized only with respect to optical power. For DOP < 1 (or DOP = 0) they appear inside (or in the center of) the Poincaré sphere.
- Non-normalized: Stokes vectors are normalized only with respect to a user-defined power value, 1 mW by default. This means that DOP and optical power determine the length of the displayed Stokes vector up to a maximum length of 1.

Memory exponent (ME)

The memory exponent (ME) defines the size of the internal memory block that is being written into. The smallest block is achieved with ME=10 (2^{10} = 1024 samples). The largest block is achieved with ME=26 (2^{26} = 67,108,864 samples).

The memory recording time is derived from ME, ATE and the sampling time 10 ns. At highest speed (ATE=0), the memory is filled within 0.67 seconds, since $2^{26}\cdot 2^{0}\cdot 10$ ns = 0.67 s.

Register description

Basic functions of the PM1000 are configured using the front control buttons. Advanced functions can be controlled through the USB or SPI port by reading and writing to internal registers, which are described in the following table. Note that the register addresses have an offset of 512. This allows a Novoptel PM1000 polarimeter and EPS1000 polarization scrambler/transformer to be connected to a shared single SPI port. All undefined registers are reserved and should not be written into.

Register address	Name	Bit(s)	Read/ Write	Function
512+0	ALM			Internal alarm code. The alarm can be cleared by writing “0” to this register. This is successful only if the alarm condition is no longer present.
		0	R/W	Alarm condition present.
		1	R/W	Optical input over range.
		2	R/W	Optical input under range.
		4	R/W	Critical board temperature.
512+1	ATE	9..0	R/W	Averaging time exponent (ATE), integer range 0 to

				20.
512+2	PC1	15..0	R	Photocurrent 1, 16 bit unsigned, averaged according to ATE.
512+3	PC2	15..0	R	Photocurrent 2, 16 bit unsigned, averaged according to ATE.
512+4	PC3	15..0	R	Photocurrent 3, 16 bit unsigned, averaged according to ATE.
512+5	PC4	15..0	R	Photocurrent 4, 16 bit unsigned, averaged according to ATE.
512+6	LPC2	15..0	R	Latched copy of photocurrent 2, updated on any read of PC1.
512+7	LPC3	15..0	R	Latched copy of photocurrent 3, updated on any read of PC1.
512+8	LPC4	15..0	R	Latched copy of photocurrent 4, updated on any read of PC1.
512+9	PCFP	15..0	R	Floating point position of photocurrent 1 to 4, updated on any read of PC1.
512+10	S0uWU	15..0	R	Input power in µW, integer part.
512+11	S0uWL	15..0	R	Input power in µW, fractional part. Updated at last read of S0uWU.
512+12	S1uWU	15..0	R	S1 of Stokes vector normalized to 1 µW, integer part. Offset=2^{15}.
512+13	S1uWL	15..0	R	S1 of Stokes vector normalized to 1 µW, fractional part. Updated at last read of S1uWU.
512+14	S2uWU	15..0	R	S2 of Stokes vector normalized to 1 µW, integer part. Offset=2^{15}.
512+15	S2uWL	15..0	R	S2 of Stokes vector normalized to 1 µW, fractional part. Updated at last read of S2uWU.
512+16	S3uWU	15..0	R	S3 of Stokes vector normalized to 1 µW, integer part. Offset=2^{15}
512+17	S3uWL	15..0	R	S3 of Stokes vector normalized to 1 µW, fractional part. Updated at last read of S3uWU.
512+18	LS1uWU	15..0	R	Latched copy of S1uWU, updated on any read of S0uWU
512+19	LS1uWL	15..0	R	Latched copy of S1uWL, updated on any read of S0uWU
512+20	LS2uWU	15..0	R	Latched copy of S2uWU, updated on any read of S0uWU
512+21	LS2uWL	15..0	R	Latched copy of S2uWL, updated on any read of S0uWU
512+22	LS3uWU	15..0	R	Latched copy of S3uWU, updated on any read of S0uWU
512+23	LS3uWL	15..0	R	Latched copy of S3uWL, updated on any read of S0uWU
512+24	DOPSt	15..0	R	Degree of polarization (DOP), 16 bit unsigned, 15 fractional bits
512+25	S1St	15..0	R	S1 of Stokes vector “Standard Normalization”, 15 fractional bits. Offset=2^{15}.
512+26	S2St	15..0	R	S2 of Stokes vector “Standard Normalization”, 15 fractional bits. Offset=2^{15}.
512+27	S3St	15..0	R	S3 of Stokes vector “Standard Normalization”, 15 fractional bits. Offset=2^{15}.
512+28	LS1St	15..0	R	Latched copy of S1St, updated on any read of DOPSt

512+29	LS2St	15..0	R	Latched copy of S2St, updated on any read of DOPSt
512+30	LS3St	15..0	R	Latched copy of S3St, updated on any read of DOPSt
512+31	DOPEx	15..0	R	Degree of polarization (DOP), 16 bit unsigned, 15 fractional bits
512+32	S1Ex	15..0	R	S1 of Stokes vector “Exact Normalization”, 15 fractional bits. Offset=2^{15}.
512+33	S2Ex	15..0	R	S2 of Stokes vector “Exact Normalization”, 15 fractional bits. Offset=2^{15}.
512+34	S3Ex	15..0	R	S3 of Stokes vector “Exact Normalization”, 15 fractional bits. Offset=2^{15}.
512+35	LS1Ex	15..0	R	Latched copy of S1Ex, updated on any read of DOPEx
512+36	LS2Ex	15..0	R	Latched copy of S2Ex, updated on any read of DOPEx
512+37	LS3Ex	15..0	R	Latched copy of S3Ex, updated on any read of DOPEx
512+38	EPow	15..0	R/W	Reference power level in µW for non-normalized Stokes vectors to reach a length of 1.
512+39	S1Nn	15..0	R	S1 of Stokes vector “Non-normalized”, 15 fractional bits. Offset=2^{15}.
512+40	S2Nn	15..0	R	S2 of Stokes vector “Non-normalized”, 15 fractional bits. Offset=2^{15}.
512+41	S3Nn	15..0	R	S3 of Stokes vector “Non-normalized”, 15 fractional bits. Offset=2^{15}.
512+42	LS2Nn	15..0	R	Latched copy of S2Nn , updated on any read of EPow
512+43	LS2Nn	15..0	R	Latched copy of S2Nn , updated on any read of EPow
512+44	LS3Nn	15..0	R	Latched copy of S3Nn , updated on any read of EPow
512+46	SlNrm	1..0	R/W	Stokes parameters/vector normalization mode, see section *Fundamental PM1000 configuration.* “00”: Non-normalized “01”: Standard normalization “10”: Exact normalization
512+48 … 512+63	UCal	15..0	R/W	User calibration matrix M with elements M00, M01, M02, M03; M10, M11, M12, M13; M20, M21, M22, M23; M30, M31, M32, M33. Non-normalized Stokes vector = M · (photocurrent vector).
512+64	UCalSL	3..0	R/W	Floating point position of user calibration matrix.
512+65	SelUCal	0	R/W	“1” switches to user defined calibration matrix.
		1	W	“1” writes user calibration matrix to flash RAM.
512+67	MinFreq	15..0	R	Minimum extrapolated optical frequency in GHz/10, 16 bit unsigned.
512+68	MaxFreq	15..0	R	Maximum extrapolated optical frequency in GHz/10, 16 bit unsigned.
512+69	CurFreq	15..0	R/W	Current optical frequency in GHz/10, 16 bit unsigned.
512+70	MinCalFr	15..0	R	Minimum calibrated optical frequency in GHz/10, 16 bit unsigned.
512+71	MaxCalFr	15..0	R	Maximum calibrated optical frequency in GHz/10, 16 bit unsigned.
512+72		0	W	SDRAM write trigger. Any write of “1” to this register

				bit will trigger a recording of the sampled SOPs in the SDRAM. Recording period is defined by averaging ATE (register 512+1). 2^{ME} samples will be recorded, defined by the memory exponent ME (register 512+73).
			R	SDRAM busy. ”1” if recording is in progress.
		1	R	“1” if post-trigger data recording is in progress.
		2	R/W	Continuous cyclic memory recording enabled (1) or disabled(0)
		3	R	“1” if a full memory block was recorded since the last trigger
			W	“1” enables automatic retrigger for next memory block
		4	R	“1” if SDRAM is busy due to oscilloscope display
		5	R	“1” if SDRAM is busy due to Poincaré sphere display
512+73		4..0	R/W	SDRAM memory exponent ME (max. 26)
512+74		3..0	R/W	Negative exponent for 16 bit power vector recorded to SDRAM. The recorded data represents power in µW left-shifted bitwise by this value. The shifting reduces quantization errors when recording at low input powers.
512+75		0	R/W	“0” selects Power+Stokes to be recorded, “1” selects DOP+Stokes
		1	R	Power/DOP selection updated at last SDRAM trigger
512+76		15..0	R	Current write address of SDRAM, bits 15..0
512+77		9..0	R	Current write address of SDRAM, bits 25..16
512+78		15..0	R	The number of recorded Blocks after last SDRAM trigger
512+79		15..0	R/W	Selects a memory block
512+80		15..0	R	The stop address in the selected memory block, bits 15..0
512+81		9..0	R	The stop address in the selected memory block, bits 25..16
512+82		9..0	R/W	Maximum number of memory blocks in automatic retrigger mode. Default is 512.
512+86		0	R/W	Define reference for internal trigger signal: “0”: External Stokes vector “1”: Internal delayed Stokes vector
		6..1	R/W	Number of clock cycles for Stokes vector delay
		10..7	R/W	Exponent for clock division of Stokes vector delay
512+87		15..0	R/W	Stokes parameter 1 of external Stokes vector reference. 15 fractional bits. Offset=2^{15}.
512+88		15..0	R/W	Stokes parameter 2 of external Stokes vector reference. 15 fractional bits. Offset=2^{15}.
512+89		15..0	R/W	Stokes parameter 3 of external Stokes vector reference. 15 fractional bits. Offset=2^{15}.
512+90		15..0	R	Current internal trigger signal
512+91		15..0	R/W	Trigger threshold for internal trigger signal
512+92		0	R/W	“1” enables internal triggering.
		1	R/W	“1” enables internal gating.
		2	R/W	Internal triggering/gating: “0”: Active high/rising edge. “1”: Active low/falling edge
		3	R/W	“1” enables external triggering.

		4	R/W	“1” enable external gating.
		5	R/W	External triggering/gating: “0”: Active high/rising edge. “1”: Active low/falling edge
512+93		0	R/W	When set to “0”, this bit will become “1” after the next trigger event.
512+95		3..0	R/W	Undersampling exponent for SDRAM readout, 4 bit unsigned
512+96		0	R	Read: “1” if SDRAM to BlockRAM copy is in progress
			W	SDRAM to BlockRAM copy trigger.
512+97		15..0	R/W	Bits 15..0 of SDRAM to BlockRAM read address
512+98		9..0	R/W	Bits 25..16 of SDRAM to BlockRAM read address
512+99		15..0	R	SDRAM output word 1, unsigned 16 bit
512+100		15..0	R	SDRAM output word 2. 15 fractional bits. Offset=2^{15}.
512+101		15..0	R	SDRAM output word 3. 15 fractional bits. Offset=2^{15}.
512+102		15..0	R	SDRAM output word 4. 15 fractional bits. Offset=2^{15}.
512+104		15..0	W	Code 39293 triggers SDRAM high speed transfer.
512+105		15..0	R/W	Bits 15..0 of SDRAM high speed read address
512+106		9..0	R/W	Bits 25..16 of SDRAM high speed read address
512+107		15..0	R/W	Number of addresses to be transferred in SDRAM high speed mode.
512+128		15..0	R	Firmware version as 4 digit BCD
512+129		15..0	R	Device DNA word 3 (DNA bits 63...48) (same as read via JTAG)
512+130		15..0	R	Device DNA word 2 (DNA bits 47...32) (same as read via JTAG)
512+131		15..0	R	Device DNA word 1 (DNA bits 31...16) (same as read via JTAG)
512+132		15..0	R	Device DNA word 0 (DNA bits 15...0) (same as read via JTAG)
512+133		15..0	R	Module Serial Number
512+134		15..0	R	Maximum input power in µW
512+144 … 512+159		15..0	R	Module Type as 32 character string. Beginning at 512+144, each Register contains two bytes, representing two ASCII-coded characters.
512+186		1..0	R/W	Selects display type at connected monitor: “00” selects Poincaré sphere live view “01” selects Poincaré sphere memory view “10” selects Oscilloscope view “11” tbd
512+187		0	R/W	“1” enables automatic Poincaré sphere refresh
512+188		15..0	R/W	Automatic Poincaré sphere refresh period in milliseconds, 16 bit unsigned
512+189		15..0	W	Any write transaction to this register clears the Poincaré sphere on the connected monitor.
512+204		11..0	R/W	HDMI frame buffer pixel row
512+205		9..0	R/W	HDMI frame buffer pixel column
512+206		15..0	R	HDMI frame buffer pixel data code
512+207		0	R/W	“0” freezes HDMI frame buffer

Operation of the instrument via front control panel

The polarimeter firmware provides a cyclic menu, the keywords of which are shown on the OLED display. The menu structure is

Optical frequency
Averaging time (ATE)
Normalization mode
Sphere / Oscilloscope
Rotate H / Zoom
Rotate V / Shift
Memory exponent (ME)
Reset dark current
Factory / User calibration

The control buttons *UP* and *DOWN* let you to navigate through the menu. The control buttons *LEFT* and *RIGHT* change a selected setting or value.

Reset dark current

Especially at low input powers, recalibration of the 4 photodetector's dark currents can improve measurement accuracy. Use the *UP/DOWN* buttons to navigate through the menu until *Reset dark current* is displayed. Disable any optical input signal and press the *RIGHT* button twice. The new dark current values are then stored in the correspondent registers.

Sphere / oscilloscope

This menu item lets you select between the following display modes:

Poincaré live

The current SOP is displayed as a point in or on the Poincaré sphere. The SOPs are plotted in red if they lie on the front side of the sphere and blue if they lie on the back side. Points of past SOPs are kept in infinite persistence. According to the selected ATE (averaging) value, new points are plotted with a frequency of up to 50 MHz. Pushing the center button or rotating the sphere clears the SOPs on the sphere.

Poincaré memory

SOPs stored in the memory are being displayed. This is useful if you want to explore the evolution of a recorded SOP event in the Stokes space. If the sphere is rotated, memory data is loaded anew.

Oscilloscope

The 4 Stokes parameters stored in the memory are being plotted as curves over time to illustrate the temporal evolution of a recorded SOP event. Push the center button to trigger a new measurement.

Factory / User calibration

By default, the PM1000 uses an internal factory calibration set which is valid for the specified wavelength range. By the GUI, the user can also write/read user calibration data to/from the polarimeter which is valid for only one specific wavelength. The user calibration can be

stored permanently in the polarimeter so that it can be accessed through the polarimeter menu without a PC.

Connecting the instrument to a PC via USB

The instrument communicates by a USB IC FT232H from FTDI (Future Technology Devices International Limited, http://www.ftdichip.com).

The Novoptel PM1000 Graphical User Interface (= GUI) is compiled on a Microsoft Windows 7 64 Bit system.

Installing the USB driver

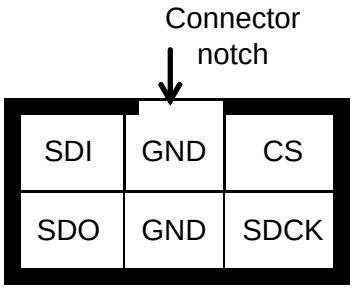
Execute the installation program of the provided USB driver (*CDM v2.10.00 WHQL Certified.exe*). You will find more detailed information about the driver at http://www.ftdichip.com/Support/Documents/InstallGuides.htm.

Connecting the instrument

After the driver is installed successfully, connect PC and instrument using the provided USB cable. Wait until Windows has recognized the USB device and shown an acknowledgement message. Power the instrument with the provided power supply and switch it on.

Interfacing the instrument via SPI

All internal registers can also accessed by SPI. The SPI interface allows communication with much lower latency than USB. The SPI connector at the backside of the device provides the following connection:



Transmission starts with falling edge of CS and ends with rising edge of CS. After falling edge of CS, the command is transmitted. SDI is sampled with rising edge of SCK. Maximum SCK frequency is 500 kHz. Command and data word length is 16 bit each. MSB of command and data word is sent first, LSB last. If a valid *register read* (RDREG) command is received, the SDO output register shifts with falling edge of SCK to transmit the requested data word. Otherwise SDO remains in high impedance state. Data transfer to the device continues directly after transmitting a *register write* (WRREG) command.

Serial interface (SPI) commands

Command	Code	Data	Function
RDREG	0XXXh	OUT	Read register XXXh (for definition see *USB section*)
WRREG	1XXXh	IN	Write register XXXh (for definition see *USB section*)

Serial interface (SPI) timing

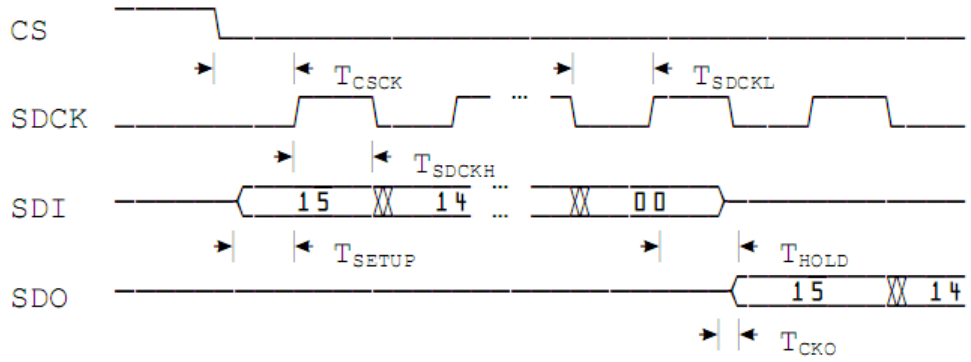


Fig. 2: Timing of SPI port.

Symbol	Description	Min	Max	Units
T_{CSCK}	CS low to SDCK high	120	–	ns
T_{CKCS}	SDCK low to CS high	120	–	ns
T_{SDCKL}	SDCKL low time	1	–	µs

T_{SDCKH}	SDCKL high time	1	–	µs
T_{SETUP}	SDI egde to SDCK high (setup time)	30	–	ns
T_{HOLD}	SDCK to SDI edge (hold time)	30	–	ns
T_{CKO}	SDCK edge to stable SDO	–	100	ns

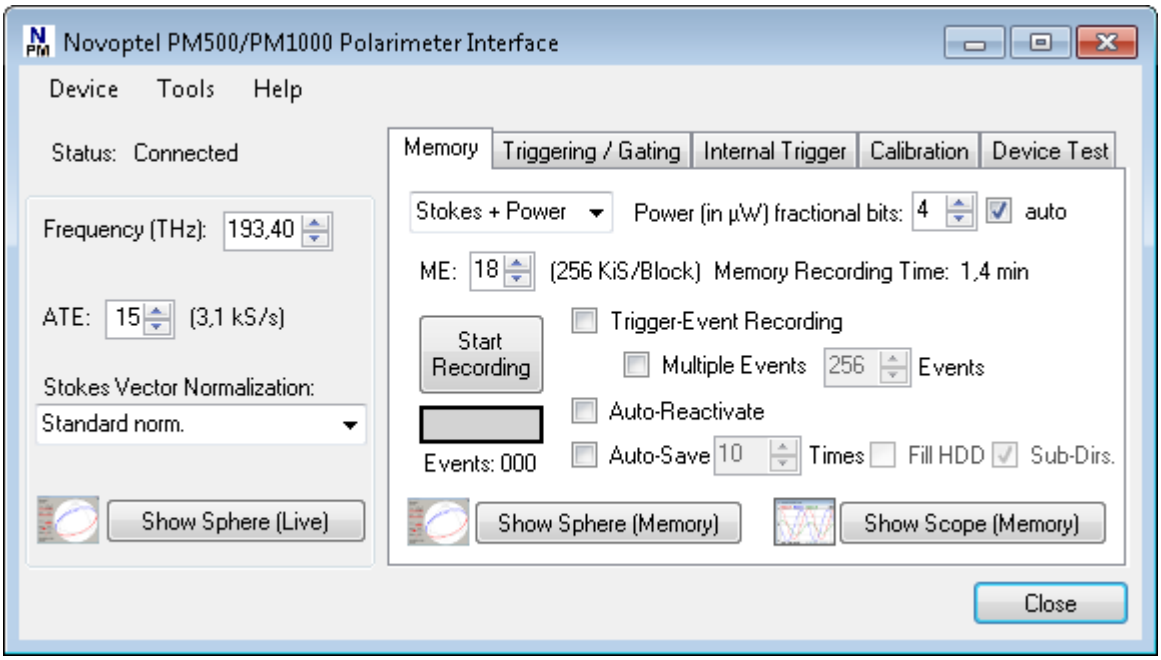
Operation of the instrument via graphical user interface

Installing the GUI

Any previous version of the graphical user interface has to be uninstalled first. For installation, execute *setup.exe* in the folder *PM_GUI_XXXX*. Follow the instructions of the installation dialogue.

If not found on the PC, Microsoft .NET Framework 4.5 will be installed during installation of the GUI. In addition, the Visual Basic Power Packs will be required to be installed. They can be downloaded using the following link:

http://go.microsoft.com/fwlink/?LinkID=145727&clcid=0x804

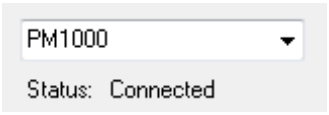


The software launches automatically after installation. If you want to launch the software later manually, select *Programs\Novoptel\PM_GUI* from the Windows Start Menu.

Basic operation

Selecting one of the attached instruments

If you have attached only one Novoptel polarimeter, the GUI automatically selects this one. If you have attached more than one instrument, select the desired one from the drop-down list in the menu strip “Device”->”Connect”.

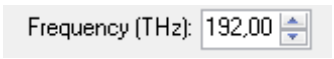


Subsequently, you can launch further instances of the GUI and connect them to further instruments.

Setting the optical frequency

Type the optical frequency in THz with up to two positions after decimal point into the field besides *Frequency* and press Enter or tune the frequency with the up and down buttons.

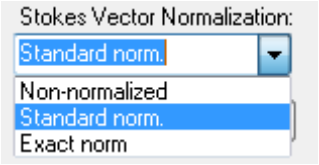
Outside the calibrated frequency range, the polarimeter matrix will be extrapolated. Measurements in the extrapolated range will be less accurate than in the calibrated range. If a frequency in the extrapolated range is selected, a warning message will be displayed.



Setting the averaging time exponent (ATE)

Type any valid ATE value between 0 and 20 into the box and press Enter or adjust the ATE with the up and down buttons. The resulting conversion rate is displayed at the right of the box.

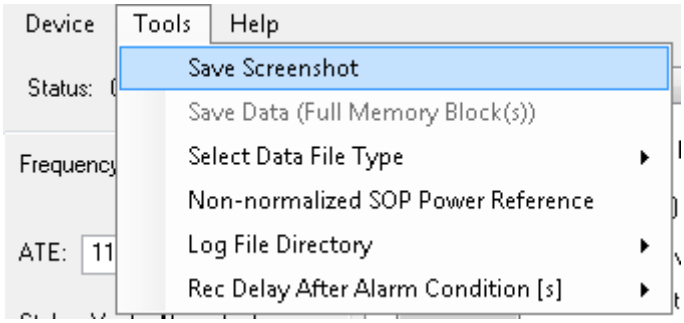
Selection of a normalization mode



Select the desired normalization mode from the drop-down list.

Save a screenshot

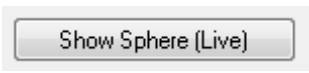
A screenshot of the current picture that is displayed at the monitor connected to the PM1000 can be saved on the PC in .png format.



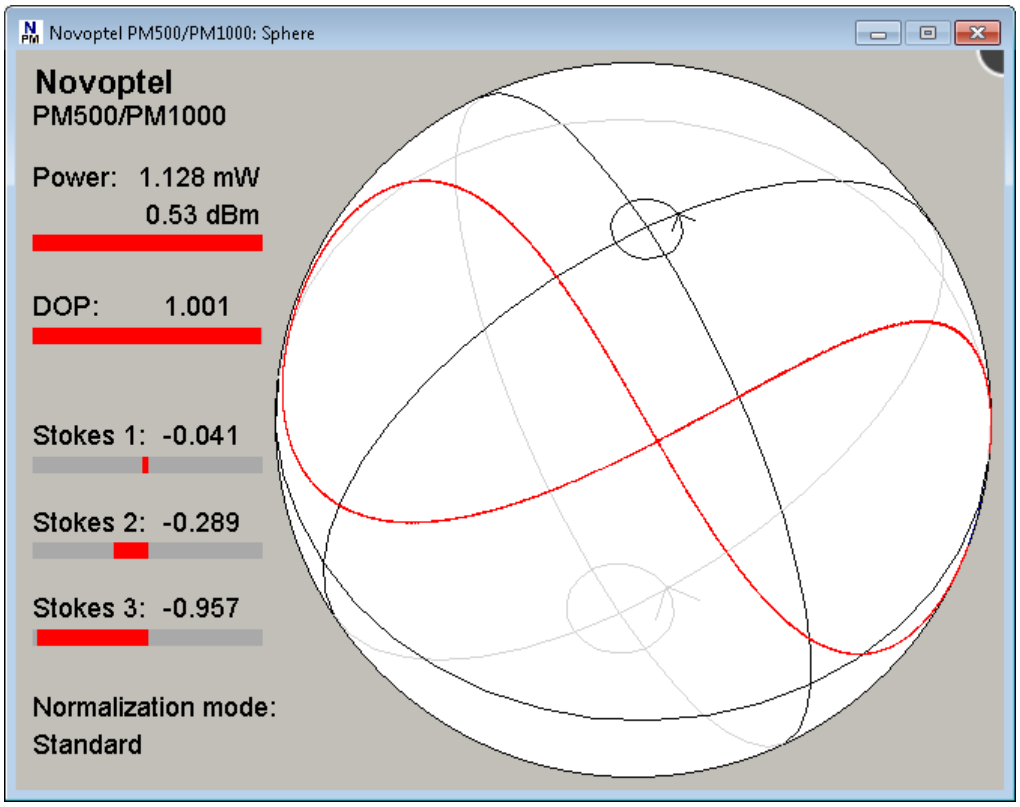
To do so, select *Tools->Save Screenshot* from the menu strip and select a target folder on your hard disk.

Poincaré sphere display

At a reduced sampling rate of 1 to 2 kHz depending on processing power of the host PC, the actual SOP samples can be displayed in the GUI. A new window is opened after pressing *Show Sphere (Live)*.



The sphere window can be resized by moving the window corners with the mouse. Power, degree-of-polarization (DOP) and the three Stokes parameters are displayed as color bars and text.

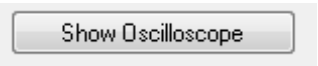


The orientation of the Poincaré sphere can be changed by moving the mouse with left button pressed. In the upper right corner, a pause/play symbol can be pressed to freeze/release the display. The endless plotting of SOPs can be paused by clicking on the *Pause* sign which appears when moving the mouse into the upper right corner.

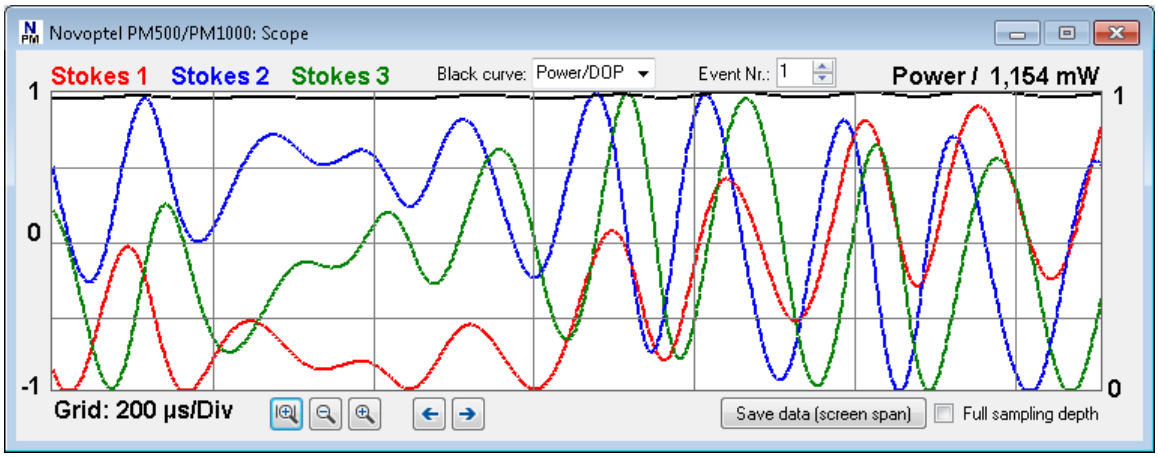
The sphere window can also be used to display SOP samples that have previously been stored in the PM1000 internal memory. This is done by pressing *Show Sphere (Memory)* instead of *Show Sphere (Live)*. After every window resize or sphere rotation, the memory will be loaded again. The loading progress is displayed in the lower right corner.

Oscilloscope plot

The stored Stokes parameters can also be displayed in an oscilloscope plot over time by pressing *Show Oscilloscope*.

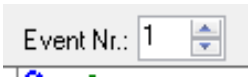


Four traces are being plotted in the new window: The three Stokes parameters S_1-S_3 plus either power or DOP, whichever has been selected for memory recording, see section *Memory configuration*. In the plot, the DOP will be normalized to 2, which means that a DOP of 1 will appear in the middle of the y-range. The power curve will be normalized to the maximum value in the data set. The value is displayed in mW in the top right corner of the plot.

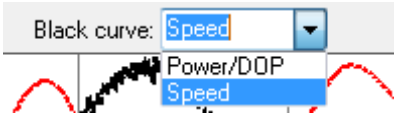


The plot can be zoomed in/out and shifted right and left. To restrict loading time, only 2048 samples are being displayed. If the memory contains more data, it is undersampled accordingly. For a full oscilloscope plot of large memory areas, up to 67 M SOPs, the oscilloscope plot displayed on the monitor connected to the PM1000 can be used.

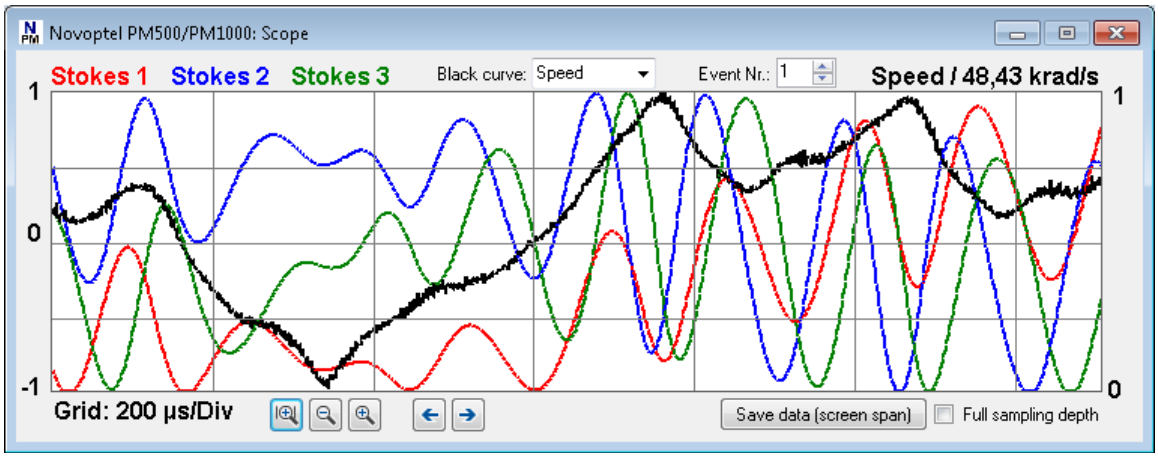
When more than one SOP event has been recorded, the different events can be selected for plotting by up and down buttons:



The GUI oscilloscope plot allows to derive the SOP changing speed from the stored SOP samples.



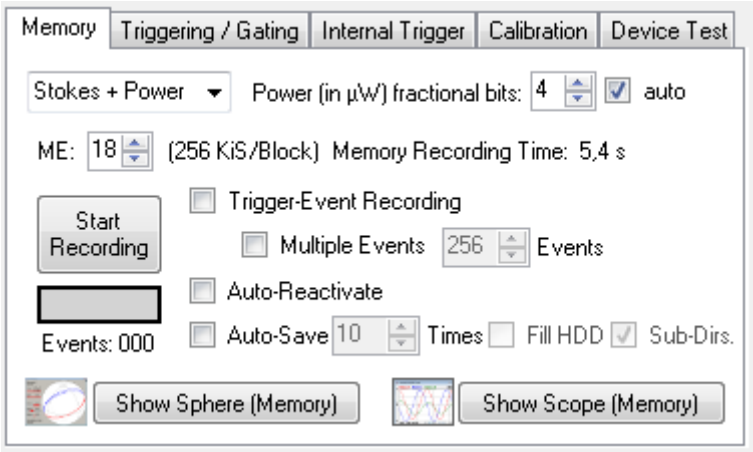
After selecting *Speed* from the drop-down list, the black curve in the plot will show the SOP speed instead of Power or DOP. The SOP speed plot is normalized to its maximum, which is displayed at the upper right of the plot. Since the SOP speed is calculated sample-to-sample, it will contain a lot of noise when observing slow SOP changes with small ATE.



For deeper SOP analysis with other programs like Matlab, the data displayed in the oscilloscope plot can be stored into a file on the computer by pressing *Save data (screen span)*. If the checkbox *Full sampling depth* is activated, the memory will not be undersampled again and every stored sample will be copied to the computer.

Memory configuration

The PM1000 internal memory allows to store up to 67 M SOP samples at a rate of up to 100 MS/s. It is configured in the *Memory* tab of the main tab control.



Memory exponent

The block size of the memory is defined by a memory exponent between 10 and 26, see section *Fundamental PM1000 configuration*. The memory recording time, derived from block size and averaging time, is displayed accordingly.

Power or DOP recording

The memory stores 4 Stokes parameters at once. For the parameter S_0, the GUI allows to select either optical power or degree-of-polarization (DOP) for recording. If power is selected, the unit of S_0 will be µW. To increase accuracy, the 16 bit integer value can be shifted bitwise to add some fractional bits before recording. If the option *auto* is selected, the number of fractional bits will be selected automatically according to the current input power level.

Data file types

The data can be saved in binary or text file format. The binary format uses less disk space and works faster, whereas the text format allows an easier processing of data with external programs. The data type can be chosen in the menu strip *Tools->Select Data File Type.*

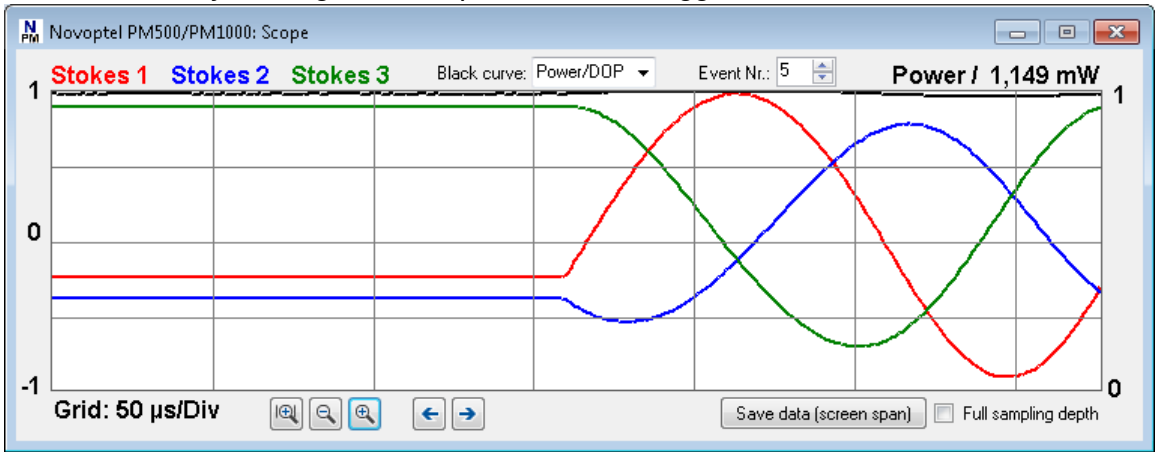
Both file types start with an ASCII text header for additional data, e.g. sampling and averaging time. Sample scripts for opening and plotting data in Matlab can be provided by Novoptel. They are described in the end of this document.

Trigger-event recording

A measurement is started by pressing the button *Activate*. In normal recording mode, the measurement stops when the memory block is filled completely or when the button is pressed again.

The checkbox *Trigger-Event Recording* enables the continuous, cyclic recording mode. In this mode, the measurement process is repeated without interruption until a trigger event occurs. This trigger event can be launched from an internal or external signal, see next section. After a trigger event, half of the block size is still recorded. In the block data loaded

from the memory starting at the stop address, the trigger event will be in the middle.



To stop the recording immediately, the button *Activate* can be pressed a second time.

If the checkbox *Multiple Events* is activated, the recording will continue in the next memory block after the post-trigger data of the first event has been recorded. The number of events to be recorded can be selected. The maximum number of events depends on the memory block size defined by ME. At ME up to 17, the maximum is 512. At larger ME the maximum is 2^{26-ME}. This means that at an ME of 26 (whole memory as one block), only one event can be recorded.

If multiple events have been recorded, the *Tools->Save Data* option from the menu strip will store each event in a separate file. The *Save data (screen span)* option in the scope window will only store the event that is currently displayed.

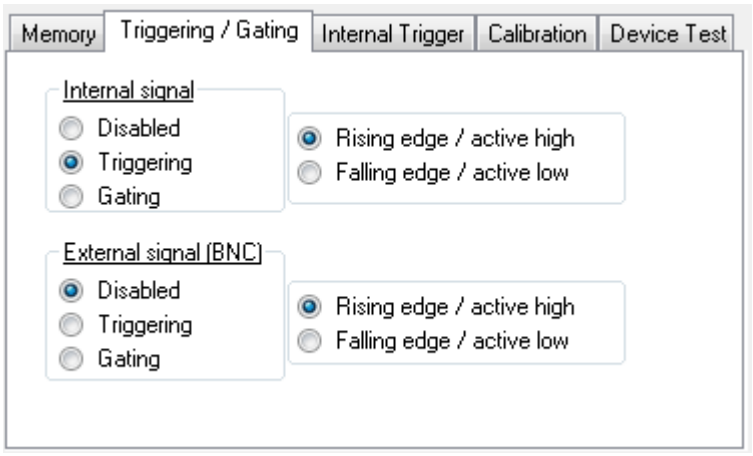
Auto-reactivated recording and storing

For automated measurements, the GUI allows to automatically store the measurement data in a file and re-activate the measurement. The number of activations generated in this mode can be defined between 1 and 1000. If multiple events are recorded during each activation, multiple files will be stored after each recording.

If the checkbox *Fill HDD* is activated, the number of files created is only limited by disk space. Even if there is disk space available, Windows sometimes blocks file creation in directories that already contain many ten thousand files. If the checkbox *Sub-Dirs* is activated, the GUI will create a new directory at the beginning of a measurement and every time the current directory is blocked.

Triggering and gating

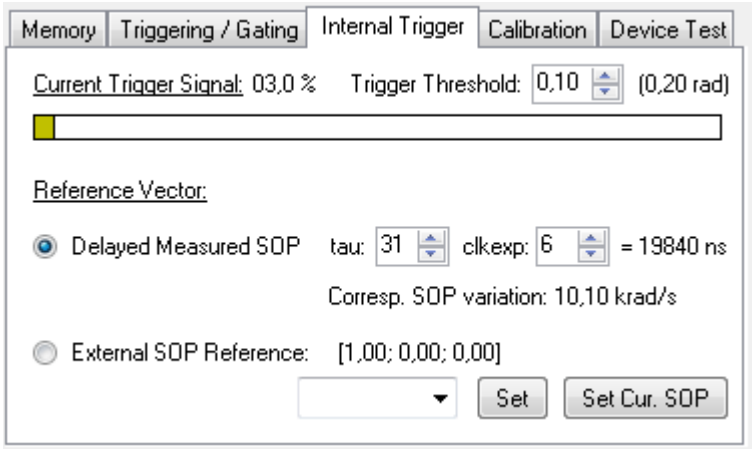
The *Triggering / Gating* tab of the GUI allows to enable triggering or gating of the memory recording. Triggering means that the cyclic measurement process is stopped after recording of post-trigger samples. Gating means that the recording process will be paused as long as the gating signal is active.



The internal triggering / gating signal is the result of an internal Stokes vector multiplication, see next section. The external triggering / gating signal is a LVCMOS33 (0 V / +3.3 V) signal that is applied to the BNC connector at the rear panel of the instrument.

Internal trigger configuration

The internal trigger signal can be configured in the *Internal Trigger* tab of the GUI. This signal is the length of a difference vector between the current and a reference Stokes vector, normalized to a maximum of 1. It is therefore a function of the angle δ between the two Stokes vectors: Trigger threshold = $0.5 \cdot |\, S_{cur}\text{-}S_{ref} \,| = \sin(\delta/2)$. For small δ it holds trigger threshold $\approx \delta/2$.



The trigger threshold can be adjusted between 0 (always trigger) and 1 (never trigger) in steps of 0.01.

Delayed measured SOP for reference

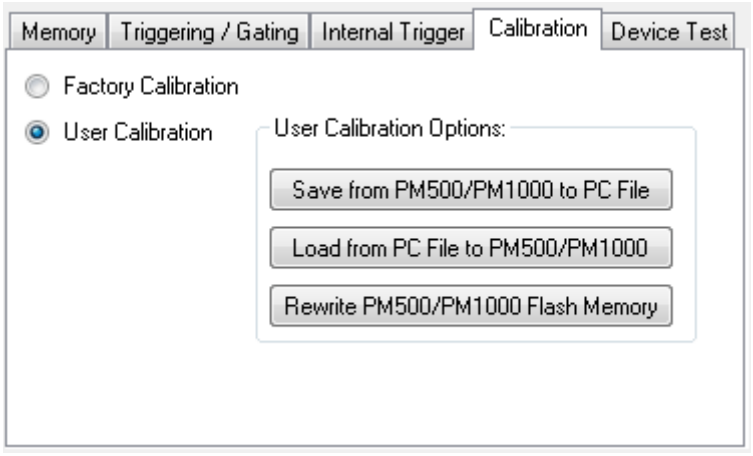
The reference Stokes vector can be a copy of the permanently measured SOP that has been delayed by a specified time. The delay time is specified by the number of clock cycles, *tau*, and an exponent for clock division, *clkexp*. Based on an initial clock period of 10 ns, the delay T_d can be calculated by $T_d = 10\ \text{ns} \cdot tau \cdot 2^{clkexp}$. By the angle δ and the time T_d, a certain SOP changing speed δ/T_d is specified. The PM1000 will be triggered whenever the optical input signal surpasses this speed. Please note that for correct operation, the delay time should always be longer than the averaging time (set by ATE).

External (user-specified) SOP for reference

It is possible to define an arbitrary Stokes vector as reference. To do so, enter three Stokes parameters, separated by semicolons, in the text field of the drop-down box and press *Set*. The Stokes vector will be normalized and transmitted to the polarimeter. One can also select one of the predefined Stokes vectors from the drop-down list. Or, set the current measured SOP as reference by pressing the button *Set Cur. SOP*.

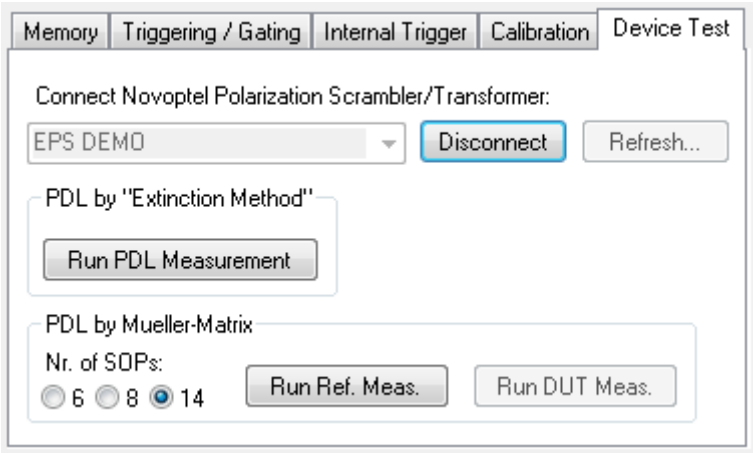
User calibration set

By default, the internal factory calibration set is used. Using the GUI a user calibration set can be loaded to and from the polarimeter. It can also be stored in the polarimeter's permanent memory (Flash) to be able to access it without GUI.



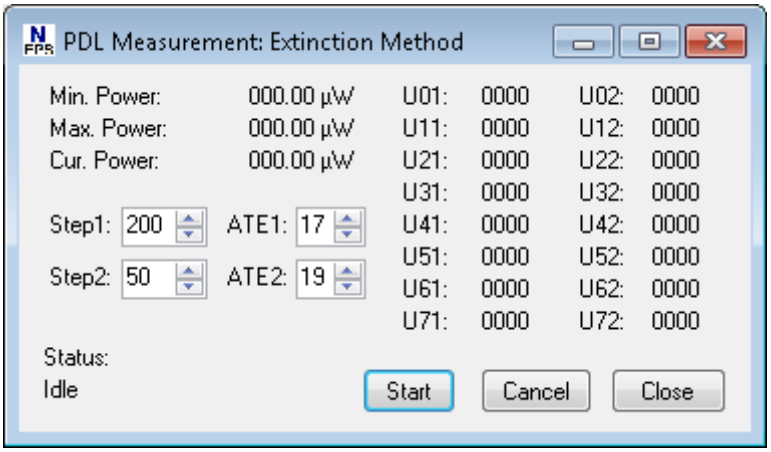
Device Test

If available, a Novoptel polarization scrambler/transformer (e.g. EPS1000 or EPX1000) can be controlled by the GUI to measure polarization dependent loss (PDL) and the Mueller matrix of a connected device under test.

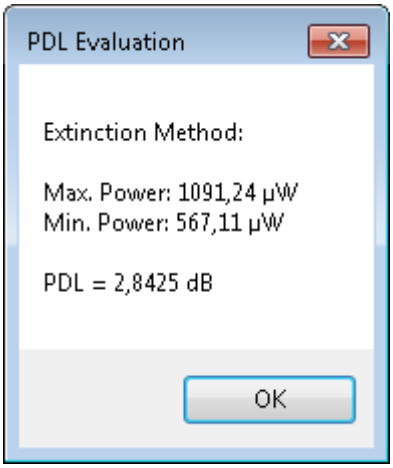


PDL by Extinction Method

If PDL is measured by *Extinction Method*, the polarization scrambler/transformer is driven to obtain the polarization states where minimum and maximum transmissions are reached. From minimum and maximum transmission, PDL can be calculated.



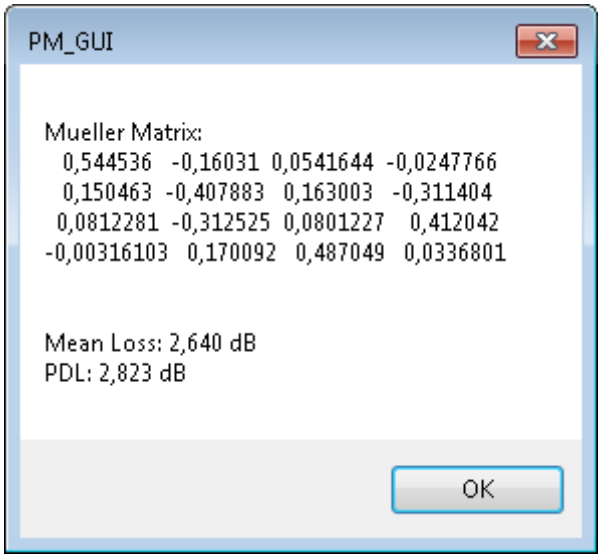
Starting at “0”, all 16 electrode voltages are modified subsequently. Step size and averaging time can be selected separately for the first and last 8 voltages. After measuring the optical power at maximum and minimum transmission, the calculated PDL will displayed.



PDL by Mueller matrix

PDL can also calculated from the Mueller matrix of a DUT. To measure the Mueller matrix of a DUT, first a number of voltage sets that lead to predefined polarization states have to be found. Examples for such polarization states are the corners of diamonds, cubes and other polyhedrons. The GUI allows to choose between 6, 8 and 14 polarization states, where “6” corresponds to the 6 normal vectors on the surface of a cube, “8” corresponds to the 8 corners of this cube, and “14” is a combination of the two.

With a patch cord connected between scrambler/transformer and polarimeter instead of the DUT, the GUI searches for the corresponding number of voltage sets after you have clicked on *Run Ref. Meas*. After the DUT has been connected again, the *DUT Measurement* can be started. In order to get appropriate results, the input polarization to the scrambler/transformer must not change between Reference and DUT measurement. After the DUT measurement has finished, the Mueller matrix and the calculated PDL are displayed.



Using Matlab to analyze stored data

As described in the sections above, the GUI allows storing the measured data in form of text or binary files. These files can be opened for further investigation by Matlab in an easy way.

The files start with a header that contains the measurement meta data. The header is formatted in such a way that it can directly be evaluated by Matlab after the hash ("#") signs are removed:

```
# Timestamp='2015.07.21 16:22:16:698';
# ATE=9;
# SamplePeriod_ns=5120;
# ME=10;
# Normalization=0;
# CyclicRecording=1;
# TriggerConfiguration=828;
# TriggerThreshold=2621;
# Data1Name='Power';
# PowerLeftShift=5;
```

In binary files, the length of the header is given by the variable *headerlength*, which itself stands at the beginning of the header. It is at least 256. This means that the first 256 bytes of the file (or more, if *headerlength* is larger) represent text in ASCII format which should be evaluated to get the measurement meta data. The measurement data starts after the header at byte number 256 (if header bytes are counted from 0 to 255). The variable *Timestamp* is a timestamp at the beginning of data transfer. With a time offset between 0 and ~100 ms, this refers to the moment of the last recorded sample. In cyclic (triggered) recording mode, this timestamp can be used to estimate the triggering moment with an uncertainty of about 100 ms when the duration of post-trigger data sampling is subtracted. *ATE*, *ME* and *Normalization* refer to the selected settings of the same name. *SamplePeriod*_ns is the sample period in nanoseconds, derived from ATE and any undersampling. When the PM1000 is in cyclic (triggered) recording mode (*CyclicRecording*=1), *TriggerConfiguration* refers to the trigger signal configuration register (512+86) and *TriggerThreshold* is the value of the trigger threshold register (512+91). *Data1Name* is either "Power" or "DOP", depending on the data selection for S0. When "Power" is selected, the value *PowerLeftShift* determines the amount of fractional bits in the data of S0.

In contrast to binary files, the byte length of the header in text files is not specified. Hence the variable *headerlength* is missing. Instead, all lines of the header begin with a hash sign to distinguish header from subsequent measurement data.

Read data from text files

The measurement data in text files are comma-separated values that also allow opening the file in Excel for instance. The following Matlab function will open a text file and plot the contained data:

```
% This is to plot the stokes parameters loaded from a Novoptel PM1000 polarimeter
% GUI version 1.0.1.8
% Copyright 2015 Benjamin Koch, Novoptel GmbH

function pm1000plot(filename)

% open the data file
FID=fopen(filename);

% get the meta data
C=textscan(FID, '#%s', 'Delimiter', '@');

% load information from meta data
if length(C{1})>0,
   for ii = 1:length(C{1}),
      try eval(C{1}{ii})
      catch err
         disp(sprintf('ERROR: Unknown command: %s', C{1}{ii}));
      end
   end
end

% get the stokes values
NN=textscan(FID,'%f,%f,%f,%f');

% close the data file
fclose(FID);

for ii=1:4,
   N(ii,:)=NN{ii};
end;

% remove offset from stokes parameters 1..3
N(2:4,:)=N(2:4,:)-2^15;

% plot the data
x=(1:length(N(1,:))) * SamplePeriod_ns*10^-9; % X-Axis in seconds
%x=(1:length(N{1})); % X-Axis as samples
plot(x, N(1,:)/2^15, '.:k', x, N(2,:)/2^15, '.:r', x, N(3,:)/2^15, '.:b', x, N(4,:)/2^15,
'.:g');
legend(Data1Name, 'Stokes 1', 'Stokes 2', 'Stokes 3');
xlabel('Seconds');
```

Read data from binary files

The following Matlab function will open a binary file and plot the contained data:

```
% This is to plot the stokes parameters loaded from a Novoptel PM1000 polarimeter
% GUI version 1.0.1.8
% Copyright 2015 Benjamin Koch, Novoptel GmbH

function pm1000plotbinary(filename)

% open the data file
FID=fopen(filename);

% get the header length (mimimum 256 bytes)
C=fread(FID, 256, 'uint8');
headerstrings=strsplit(char(transpose(C)), char(13));
try eval(char(headerstrings(1)))
```

```
catch err
   disp(sprintf('ERROR: Unknown command: %s', char(headerstrings(1))));
   pause
end

% get the full header with meta data
fseek(FID, 0, 'bof');
C=fread(FID, headerlength, 'uint8');
headerstrings=strsplit(char(transpose(C)), char(13));
size_headerstrings=size(headerstrings);
nlines=size_headerstrings(2);

% load information from meta data
if nlines>2,
   for ii=2:nlines-1
      try eval(char(headerstrings(ii)))
      catch err
         disp(sprintf('ERROR: Unknown command: %s', char(headerstrings(ii))));
         pause
      end
   end;
end;


% get the data after the header
fseek(FID, headerlength, 'bof');
C=fread(FID, 'uint16');

% get the stokes parameters
N=reshape(C, 4, floor(length(C)/4));

% remove offset from stokes parameters 1..3
N(2:4,:)=N(2:4,:)-2^15;

% close the data file
fclose(FID);

% plot the data
x=(1:length(N(1,:))) * SamplePeriod_ns*10^-9; % X-Axis in seconds
%x=(1:length(N(1,:))); % X-Axis in samples
plot(x, N(1,:)/2^15, '.:k', x, N(2,:)/2^15, '.:r', x, N(3,:)/2^15, '.:b', x, N(4,:)/2^15,
'.:g');
legend(Data1Name, 'Stokes 1', 'Stokes 2', 'Stokes 3');
xlabel('Seconds');
```

Operation of the instrument using Matlab®

The USB driver has to be installed on your system and the instrument needs to be connected using a USB cable. Examples of Matlab communication scripts can be downloaded from http://www.novoptel.de/Home/Downloads/Matlab_Support_Files.zip

Access the USB driver

Matlab needs a header file like *ftd2xx.h* from FTDI to access the driver. Novoptel provides the header version *matftd2xx.h,* in which the data types are modified to become compatible with current Matlab versions.

You will find help about communicating to a driver at

http://www.mathworks.com/help/techdoc/ref/loadlibrary.html

The different functions of the driver can be seen from the header file. Information about each function is provided at http://www.ftdichip.com/Support/Knowledgebase/index.html

Example Matlab programs for USB data transfer are available from Novoptel upon request.

USB Settings

The following settings have to be applied within Matlab (or other programs) to enable USB communication:

Baud Rate	230400 baud
Word Length	8 Bits
Stop Bits	1 Bit
Parity	0 Bit

To speed up sequential read and write operations, we recommend setting:

USB Latency Timer 2 ms

Transfer protocol

The instrument is controlled by reading from and writing to USB registers. The register address line is 12 bits wide, while each register stores 16 bits. All communication is initiated by the USB host, e.g. the Matlab program.

Writing to a register uses a 9 byte data packet. Each byte represents an ASCII-coded character. The packet starts with the ASCII-character “W” and ends with the ASCII-code for *carriage return*.

Send *write data* packet

„W“	A(2)	A(1)	A(0)	D(3)	D(2)	D(1)	D(0)	^CR

The 12 bit register address A is sent using 3 bytes, each containing the ASCII-character of the hexadecimal numbers 0 to F which represents the 4 bit nibble. The character of the most

significant nibble is sent first. The 16 bit data, which should be written into the register, is sent with 4 bytes using the same coding as the register address.

Reading data from a register requires the host to send a *request data* packet to the instrument. The packet starts with the ASCII-character “R”, followed by the register address coded the same way as in *write data* packets.

Send *request data* packet

„R“	A(2)	A(1)	A(0)	„0“	„0“	„0“	„0“	^CR

After receiving the *request data* packet, the instrument sends the requested data packet to the host:

D(3)	D(2)	D(1)	D(0)	CR

Burst transfer

To increase transfer speed, consecutive addresses of an internal memory can be transferred at once. Additional packets are defined for this purpose:

Send *Set burst address register* packet

„X“	„0“	„0“	„0“	D(3)	D(2)	D(1)	D(0)	^CR

The data D is the address of the register that will be incremented during burst transfer. In most cases, this register will represent the read address of a memory.

Send *Set start value* packet

„X“	„0“	„0“	„1“	D(3)	D(2)	D(1)	D(0)	^CR

The data D is the start value of the counting.

Send *Set stop value* packet

„X“	„0“	„0“	„2“	D(3)	D(2)	D(1)	D(0)	^CR

The data D is the stop value of the counting

Send *Set read address* packet

„X“	„0“	„0“	„3“	D(3)	D(2)	D(1)	D(0)	^CR

The data D is the address of a register that contains the data to be sent during burst transfer. In most cases, this register will represent the data output of a memory. After sending this packet, burst transfer will start. Beginning with the start value, the address register will be incremented until it reaches the stop value. After every step, the data appearing in the read address register will be transferred to the host.

Operation of the instrument using other programs

The USB vendor http://www.ftdichip.com/Support/Knowledgebase/index.html provides examples for USB access using other programs, for example LabVIEW®. A rudimental example of a LabVIEW-VI (virtual instrument) is available from Novoptel upon request.

Firmware upgrade

Via the JTAG port the user can upgrade the firmware, if ever needed.

The schematic and timing of the JTAG port correspond to that detailed in Spartan-6 FPGA Configuration User Guide UG380 (v2.6) June 20, 2014 from Xilinx (www.xilinx.com).

Acronyms

ATE	Averaging time exponent
DOP	Degree of polarization
DUT	Device under test
DVI	Digital visual interface
FPGA	Field-programmable gate array
GUI	Graphical user interface
HDMI	High definition multimedia interface
LSB	Least significant bit
JTAG	Joint test action group
ME	Memory exponent
MSB	Most significant bit
PC	Personal computer
PDL	Polarization dependent loss
SOP	State of polarization
SPI	Serial peripheral interface
USB	Universal serial bus